Investigation of Material Combinations for Axially-Laminated Synchronous Machine

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***Abstract*—High-speed electric machines are special types of electric machines which aim for compact, direct-driven high-speed applications and highly efficient operation, especially, when gearbox can be avoided. Design of these types of machines is highly iterative combining multiphysics optimization and leads to custom types of machines which fulfill the application-specific requirements. Synchronous Reluctance Machines (SynRMs) might have an axially-laminated solid rotor structure, which combines magnetic and non-magnetic layers rigidly bonded to each other by vacuum brazing, hot isostatic pressing, soldering, explosion welding or even by additive manufacturing. In the study five non-magnetic materials and nine magnetic materials are cross compared and the results show clear differences in performance, efficiency and physical properties of the rotor when made of different material combinations, and thereby can suggest the best pairs when application-specific performance criteria are known. The study is carried out on a 12 kW machine with a maximum speed of 24000 rpm.**

***Index Terms*—Axially laminated rotor, High-speed motor, Magnetization Curves, Material Comparison, Synchronous Reluctance Motor, Solid Rotor.**

I. INTRODUCTION

HIGH-SPEED electric machines are used in applications where high rotation speed brings added value, e.g. in compressor, blower or turbine applications where a high efficiency is desired. [1] High-speed electric machines can be realized with various techniques. The surface velocity, i.e., peripheral velocity of the rotor can be used as indicative parameter for the consideration of the feasible motor technologies. High-speed machines with moderate surface velocity (i.e. below 150 m/s) can be implemented using permanent magnet (PM) topologies, interior permanent magnet (IPM) or rotor surface permanent magnet (SPM) versions. These can be realized with traditional laminated rotor construction. [2]. For higher surface speeds, induction machines (IM) with a solid rotor structure can be more feasible in practise [3]. A high-speed IM can be realized also with a slitted solid rotor to improve the electromagnetic performance in case, where magnetic steel is utilized alone in the rotor constriction. A squirrel cage can be added in a solid-steel core to further improve the motor electromagnetic characteristics. [4] However, the mechanical construction of a squirrel-cage rotor is challenging and therefore we study here if the rotor could be replaced by an axially laminated synchronous reluctance rotor.

In high-speed machines, especially high-power machines the rigidity and length of the rotor is limiting the speed and maximum achievable power, as the maximum diameter is limited by the experienced stresses and the length of the electric machine by its dynamic response (rotor and stator dynamics). [5] An increased length decreases the rotor critical speeds and yields easily to resonance problems. [6] Depending on the applied topology, the machine can be designed for sub-critical operation, i.e. below the first bending frequency or super-critical operation where the first bending frequency is passed. In super-critical applications, the passing of the bending frequency requires careful design and effective active magnetic bearing control principle to achieve it without increasing the overall vibrations. [7]

A promising alternative approach achieving a high surface velocity and high efficiency is the axially laminated anisotropic rotor shown e.g. in [8]. The axially laminated synchronous reluctance rotor can be realized with various materials. Fundamentally, a pair of compatible magnetic and non-magnetic steels is needed. In this study, different magnetic and non-magnetic materials and their performance in a high-speed electric machine are evaluated. The performance is a compromise of mechanical, electrical, thermal, and manufacturability properties of the materials, and their availability. From the mechanical perspective, low density, high yield strength, equal thermal expansion coefficient and good manufacturability are desired properties, while the costs at the same time should be acceptable. From the electromagnetic perspective, both the magnetic and non-magnetic steels should have a high resistivity to reduce eddy current losses (or very high conductivity to reduce the penetration depth of the eddy currents) and the magnetic steel should have a high magnetic permeability and high saturation flux density to increase the magnetic anisotropy of the rotor.

From thermal viewpoint, a high thermal conductivity is desired for both materials to improve the heat removal from the rotor. This enables having a low temperature gradient within the rotor and thereby reduced risk for shaft bending as a result of thermal stresses in the non-homogeneous rotor.

From manufacturability point of view, it is desired that both materials are well available, machinable to high tolerances and feasible to form a metallic contact between the material layers to ensure a rigid structure.

The main research target presented in this paper is to investigate different materials (currently applied in differ-

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ent electric motors) and their combinations in an axially-laminated synchronous reluctance machine (AlaSynRM) and to highlight the most promising design variants. Also, since the materials presented in the paper are often applied in other high-speed electrical machines, this paper can be a source of a detailed characteristics of these materials needed for reliable machine simulation. In the study, a high-speed, solid-rotor, synchronous reluctance motor performance is studied and compared when using possible materials combination in the magnetic and no-magnetic layers. The motor used for the materials comparison has a rated power of 12 kW at the rated speed of 24000 rpm. A 2D transient electromagnetic Finite Element (FE) analysis is used in the computation of the performance. The following aspects are taken into account: torque, torque ripple, efficiency, power factor, stator core losses and rotor eddy current losses.

This paper is organized as follows. The typically used materials in different high-speed motor typologies are presented in Section II with a focus on the materials physical properties. Also, applicability of these materials for the solid rotor Synchronous Reluctance Motor (SynRM) is discussed. The method for the comparison of the machine variants using different materials in rotor non-magnetic and magnetic layers are evaluated and shown in Section III. Then, the results and the comparison of the simulations are shown in Section IV. Finally, a summary of the achieved conclusions is given in Section V.

II. MATERIALS FOR HIGH-SPEED ELECTRICAL MOTOR

Selection of suitable materials for a high-speed electrical motor strongly depends on the typology of the motor; in literature it is possible to find several research publications related to the design of high-speed Induction motors (IMs) [8]–[10], permanent magnet motors [11]–[15], and Synchronous Reluctance Motors (SynRMs) [8], [16]–[21]; they present different combinations of adopted materials. Table I and II show the mechanical, thermal and electrical properties of the studied magnetic and nonmagnetic materials, respectively.

Terzic et al. [9] compare several materials for a dual-stator high-speed drag cup induction motor. The stators are made from standard electrical steel, the windings using Litz copper wire in order to reduce the skin effect and for the rotor cup they propose three different materials: Cu_3-Mg (brass), Al 7075 T6 (aluminum alloy) and Be-Cu (Beryllium Copper). Abramenko et al. [8] analyze a solid-rotor induction motor rotor composed from the commercial magnetic steel S355 core equipped with copper end rings to reduce the rotor equivalent resistance and to increase the overall performance. Barta et al. [10] compare different materials both for a solid rotor and for a laminated one, but it is concluded that to reach a very high peripheral speed it is not possible to use a laminated rotor. For the solid rotor they also propose to use the Glidcop family or Beryllium-Copper materials which have higher mechanical strength compared with ordinary copper. For the magnetic materials, the commonly available grades of 41CrAlMo7, 41CrMo4, and S355J were compared and for more demanding applications the AerMet and Marage families can be implemented. They were originally developed for military aircraft applications.

In high-speed Permanent-Magnet (PM) motors the trend shown in [11]–[15], is to use a 2-pole rotor with a sleeve to maintain the magnet in place at a high speed. The typical magnet type used for high speed motors is Sm_2Co_{17} because of its capability to operate at elevated temperatures (above 150 °C), while for the sleeve three different materials are proposed: Inconel 718, carbon fibers and titanium alloy.

On the other hand, in literature several topologies for the SynRMs are presented starting from the use of laminated rotor core (in which the peripheral speed is below 150 m/s) optimized for minimizing the impact of the inner ribs [16], or resin aided ribless solutions [17] (peripheral speed of 50 m/s), [18] (peripheral speed of 125 m/s) to guarantee the mechanical integrity without affecting the electromagnetic performance. Another possible solution to obtain a ribless structure is the adoption of a dual phase material by using magnetic and nonmagnetic layers in the rotor [19] (peripheral speed of 100 m/s); with all these solutions it is not possible to reach an ultra-high speed. In order to reach higher peripheral speeds, solid-rotor solutions have to be used. Ikäheimo [20] proposes a new concept for the solid rotor motor. His design is composed by a round iron rod array held together with a casting of Cu-Al alloy similar to Hidruax 1. This material has been chosen thanks to its availability and structural properties. Another innovative concept for the solid-rotor synchronous reluctance machine is shown in [8] and [21] and consists in metallic bonds between the nonmagnetic and ferromagnetic layers. The structure is similar to the axially laminated machine but using thicker layers. In this way it is possible to obtain a very high value of saliency ratio (higher than 10) but with a lower efficiency because this solution presents high rotor losses as a result of air-gap space harmonics and the low rotor electrical resistance. It, however, presents good values for power factor.

This work focuses on possible combinations of materials which can be used for a high-speed solid-rotor axially-laminated synchronous reluctance motor (and other motor types) that should be suitable for their mechanical (concerning a high-speed application), electrical, and magnetic properties. For the nonmagnetic layer the following materials have been chosen and compared: AISI 304, AISI 316, Creusabro, Inconel 718, and titanium; while for the magnetic layers AISI 1010, AISI 1018, AISI 1020, AISI 430, Imacro M, 34CrNiMo6, S355, X20Cr13 and 40CrMoV5-1 have been compared. The mechanical, thermal, and electrical parameters are shown in Table I and Table II while the *B-H* curves of the magnetic materials are shown in Figure 1 and Figure 2.

III. ELECTRIC MACHINE PERFORMANCE WITH DIFFERENT MATERIALS

Several combinations of magnetic and nonmagnetic materials in an AlaSynRM and the corresponding motor performance are evaluated using transient electromagnetic analysis. It also evaluates the rotor losses which are produced by

TABLE I: Magnetic materials focused in the study

Material	Modulus of Elasticity (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Density (kg/m^3)	Coefficient of linear expansion (μm/(m°C))	Electrical conductivity (MS/m)	Electrical resistivity ($\mu\Omega$m)	Thermal conductivity (W/Km)	Relative magnetic permeability
AISI 1010 (1.0032)	200	325	180	7870	12.2	6.99	0.143	51.9	Figs. 1 & 2
AISI 1018 (1.0419)	200	400	220	7870	12.2	6.29	0.159	51.9	-”-
AISI 1020 (1.0402)	186	380	205	7870	12.8	6.29	0.159	51.9	-”-
AISI 430 (1.4016)	200	531	205	7800	11.2	1.64	0.61	24.9	-”-
Imacro M	210	800	700	7800	12.0	5.00	0.20	40-45	-”-
34CrNiMo6 (1.6582)	210	1000	700	7800	12.0	5.00	0.20	40-45	-”-
S355 (1.0577)	210	550	355	7800	12.0	5.00	0.20	42.2	-”-
X20Cr13 (1.4021)	200	1720	1480	7800	11.5	1.67	0.60	30	-”-
40CrMoV5-1 (1.2344)	210	1810	1520	7780	12.3	1.84	0.543	19.2	-”-

TABLE II: Materials of nonmagnetic steels focused in the study

Material	Modulus of Elasticity (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Density (kg/m^3)	Coefficient of linear expansion (μm/(m°C))	Electrical conductivity (MS/m)	Electrical resistivity ($\mu\Omega$m)	Thermal conductivity (W/Km)	Relative magnetic permeability
AISI 304 (1.4301)	200	600	190	7900	17.0	1.37	0.73	15	1.021
AISI 316 (1.4401)	200	600	200	7980	17.0	1.33	0.75	15	1.020
Creusabro (1.3401)	190	800	380	7880	20.5	1.47	0.68	13	1.002
Inconel 718 (2.4668)	208	1407	1172	8220	13.9	0.80	1.25	11.4	1.0011
Titanium (Grade 5)	113.8	950	880	4430	9.2	0.59	1.78	6.7	1.0005

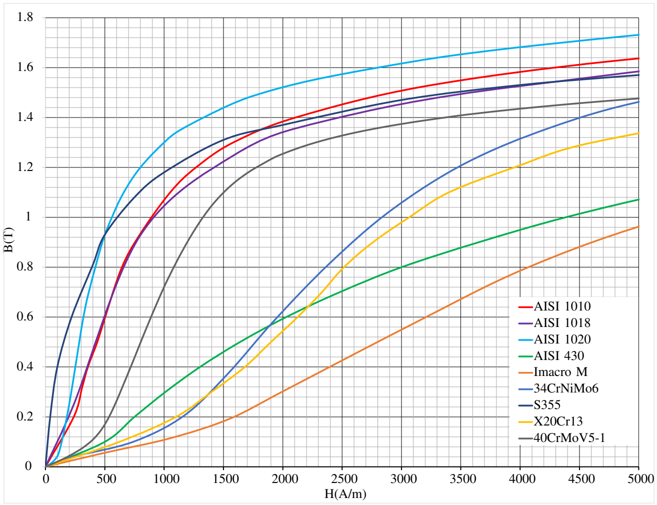


Fig. 1: *B-H* curves of the magnetic materials from 0 to 5000 A/m.

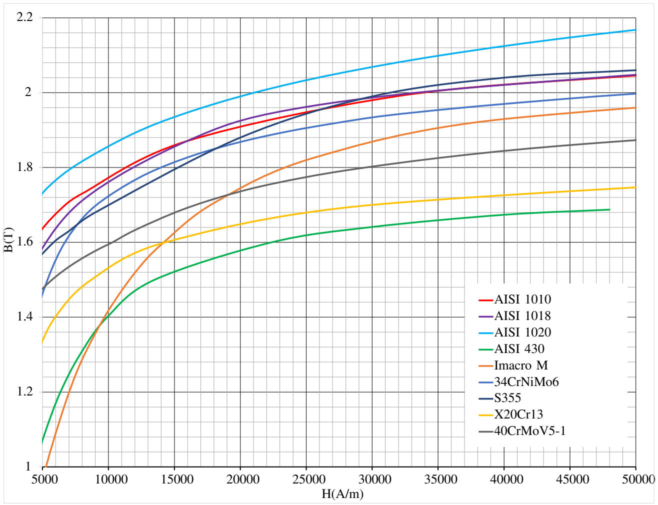


Fig. 2: *B-H* curves of the magnetic materials from 5000 to 50000 A/m.

the spatial harmonics in the machine. In order to obtain more reliable results and take into account the end effect 3D Finite Element Analysis (FEA) should be used, but the high computational time required by these kinds of simulations make it non-feasible for the comparison of several material combinations. With 2D FE-calculations the fundamental differences can be assessed. In order to obtain reliable results in a reasonable time for a conceptual design selection, it is possible to use the 2D finite element analysis and consider that all the rotor layers are connected between each other with a null resistance. This consideration might lead to slightly higher computed losses keeping a safety margin in the efficiency results [8]. This approach is suitable for the scope of the work because only the modification in the material is investigated and possible errors caused by neglecting the end effect will be present in all simulated cases, which makes the comparative study equitable.

A. Finite Element Model

To carry out the results of these simulations a commercial finite element software, Ansys Electronic Desktop - Maxwell2D has been used. Model and mesh of the designed machine are shown in Figure 3.

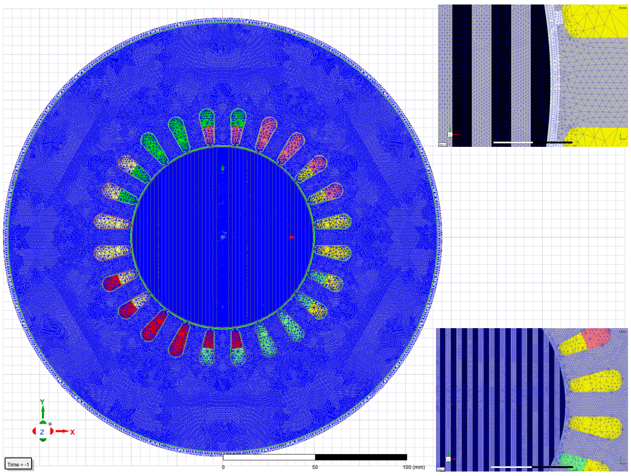


Fig. 3: Finite element model of the electric machine

The stator winding of the machine has a short pitching in order to reduce the harmonic fields in the air gap and therefore the losses in the rotor. More detailed information of the machine geometry can be found in [8]. The rotor has one central layer of magnetic material of 6.5 mm thickness and 24 non-magnetic and 22 magnetic layers of 2 mm thickness. The nominal speed of the motor is 24 000 rpm. Active part rotor diameter is 98.5 mm and nominal power is 12 kW. Surface velocity results thereby in 124 m/s. The simulations consider the stator winding delta connection with a sinusoidal line current supply as shown in Figure 4.

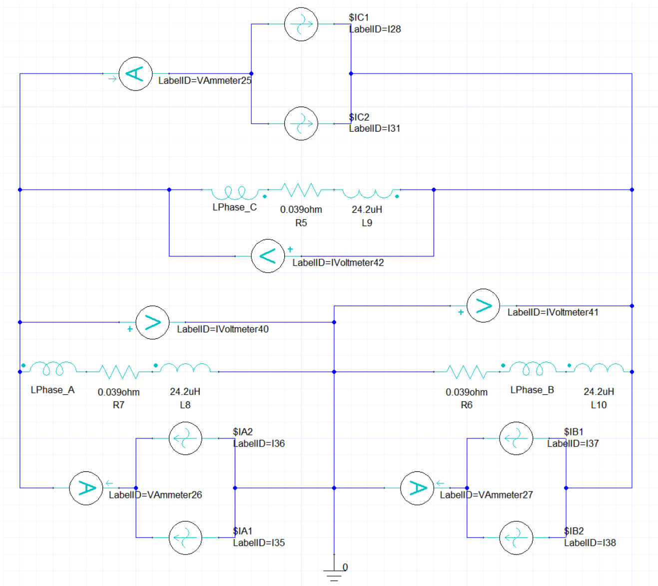


Fig. 4: Current supply for the electric machine

The delta connection leads to a third harmonic component and its multiples in the winding current even though the line current is sinusoidal. This phenomenon slightly increases the machine losses. This connection is necessary in order to avoid an increase of the supply voltage and/or an increase of the number of conductors per slot which are not possible in this case. Simulation step size has been selected as 6.25 µs, 1/400 of the value of the fundamental period, which is 2.5 ms, considering a base speed of 24000 rpm. The selected time step allows analyzing the effects of the high harmonic losses in the stator and in the rotor.

B. Results

The results in terms of flux density inside of the machine and the behavior of the phase voltage, losses, and torque are shown only for the solution which uses Inconel 718 as nonmagnetic material and S335 as magnetic one. The flux density (Fig. 5) shows that the rotor magnetic layers are not saturated and they operate with a level of flux density close to the knee of the *B*-*H* curve in order to maximize the torque guaranteeing a very high saliency ratio.

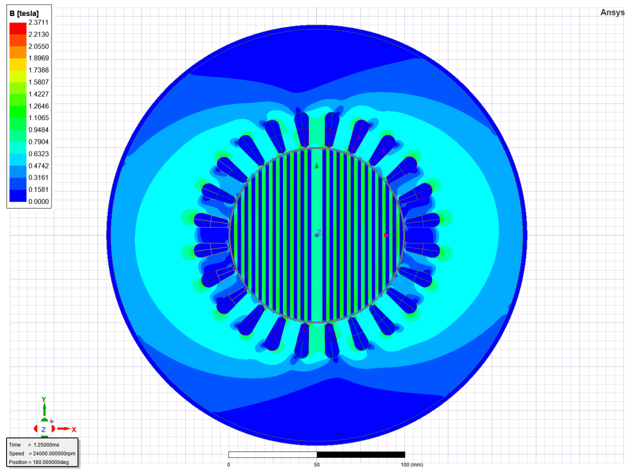


Fig. 5: Flux density at the rated working point

In the curves of the phase current and voltage (Fig. 6) it is possible to see the third harmonic in the current resulting from the delta connection, as well as high frequency current harmonics.

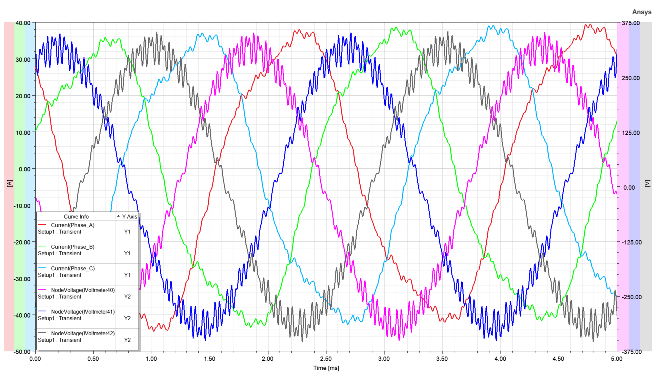


Fig. 6: Phase currents and voltages

Also the phase voltage presents a lot of harmonics which increase the losses of the machine in terms of core losses in the stator and in particular in the eddy currents in the rotor. This is visible in the figure of losses (Fig. 7) in which the rotor losses are higher than the stator ones. This kind of simulation is repeated for all combinations of the material in order to verify the impact of the modification of the material on the performance and which are the most adapt material for this kind of rotor; the comparisons are shown in the next Section.

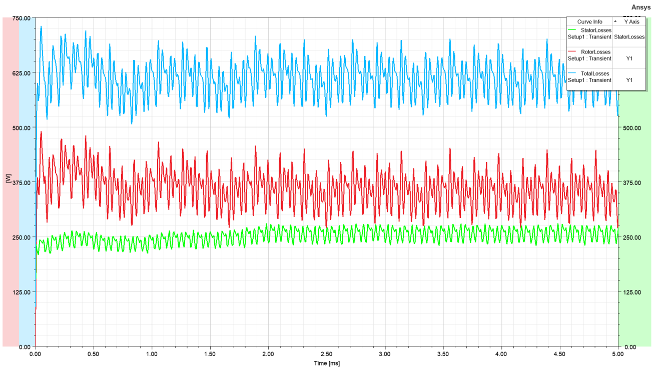


Fig. 7: Distribution of losses and total losses in the machine

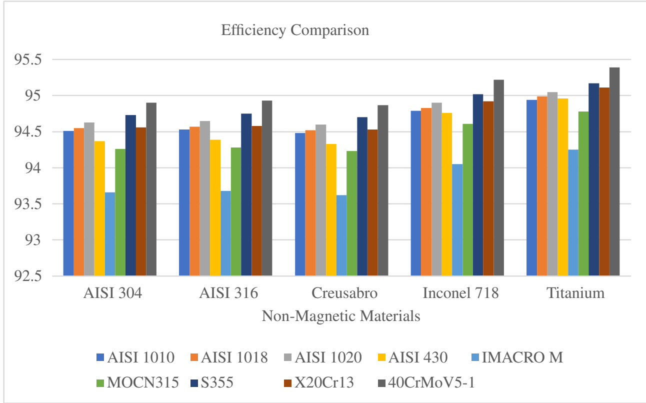
IV. Comparison of the Simulation Results

Table III shows the comparison results for different combinations of nonmagnetic and magnetic materials in terms of efficiency.

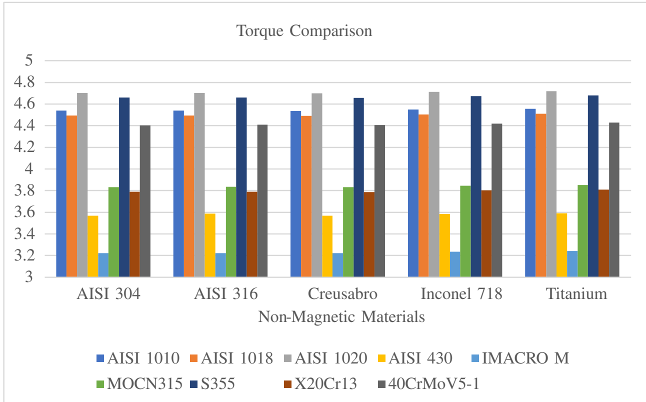
The materials that show the highest efficiency are the ones with the highest magnetic permeability; this is due to the high achievable average torque with these materials (Table IV). The results of these two tables are reported as graphs in Figures 8a and 8b in order to have better understand the comparison between the different material combinations.

Comparing materials with similar values of permeability (AISI 1010, AISI 1018, AISI 1020, and S355) the difference in the efficiency is mainly due to the value of the electrical resistivity. The S355 material is the one with the highest electrical resistivity and it shows the highest efficiency. If Orvar Supreme has been considered, despite its lower permeability compared to the other materials, thanks to its very high resistivity (54.3 $\mu\Omega$cm vs 20.0 $\mu\Omega$cm of the S355), shows the highest efficiency thanks to a significant reduction of the rotor eddy current losses. The effect of the nonmagnetic material is a variation of the rotor eddy current losses in function of its electrical resistivity. They have the same effects considering the various magnetic materials. The highest values of efficiency are reached with the highest electrical resistivity materials (Inconel 718 or Titanium). Titanium has also the advantage to have a lower density so that it can reduce the mechanical stress in the rotor and its inertia. The peak-to-peak torque mainly depends on the value of the average torque and the torque ripple of the machine (the ratio between the peak-to-peak torque and the average one) is slightly dependent upon the combination of the different materials, the maximum variation is 5%.

The results in terms of power factor of the different combinations of materials are shown in Table VI where it is possible to see that the power factor mainly depends on the



(a) Efficiency comparison



(b) Torque comparison

Fig. 8: Efficiency (a) and Torque (b) comparison with different materials

magnetic material while changing the nonmagnetic material has a negligible effect. The best material maximizing the power factor is, again, the one with the highest permeability (AISI 1020 or S355). The same effects are shown for the average torque value and peak to peak one, shown in Table V and Table VI. All of these comparison are made using the same value of input currents, but according to the material curve it is possible to carry out other considerations. Rotors that adopt S355 and AISI 1020 as magnetic steel show similar electromagnetic performance (power factor and average torque). The comparison of the BH curves of the materials indicates that AISI 1020 can reach a higher value of induction field with better overloading performance. This is because it guarantees a higher magnetic permeability, d-axis inductance value, and saliency ratio when a higher current (and flux inside the machine) is requested to increase the torque capability. Since all the materials show similar values in terms of power factor and due to the voltage limitation, if a higher speed has to be reached without modification in the stator and in the winding arrangement (for mass production issue), a low permeability material has the possibility to reach a higher speed maintaining similar level of power compared to the other solution. For example, considering IMACRO M steel it is possible to reach a speed of 33000 rpm, from the

TABLE III: Efficiency (%) with different magnetic (columns) and non-magnetic (rows) materials

	AISI 1010	AISI 1018	AISI 1020	AISI 430	IMACRO M	MOCN315	S355	X20Cr13	40CrMoV5-1
AISI 304	94.51	94.55	94.63	94.37	93.66	94.26	94.73	94.56	94.90
AISI 316	94.53	94.57	94.65	94.39	93.68	94.28	94.75	94.58	94.93
Creusabro	94.48	94.52	94.60	94.33	93.62	94.23	94.70	94.53	94.87
Inconel 718	94.79	94.83	94.90	94.76	94.05	94.61	95.02	94.92	95.22
Titanium	94.94	94.99	95.05	94.96	94.25	94.78	95.17	95.11	95.39

TABLE IV: Average torque (Nm) with different magnetic and non-magnetic materials

	AISI 1010	AISI 1018	AISI 1020	AISI 430	IMACRO M	MOCN315	S355	X20Cr13	40CrMoV5-1
AISI 304	4.540	4.493	4.703	3.568	3.222	3.833	4.660	3.790	4.402
AISI 316	4.540	4.494	4.703	3.587	3.223	3.834	4.661	3.790	4.409
Creusabro	4.537	4.491	4.699	3.568	3.222	3.831	4.657	3.787	4.405
Inconel 718	4.550	4.505	4.713	3.584	3.236	3.846	4.672	3.803	4.420
Titanium	4.557	4.511	4.719	3.591	3.243	3.852	4.679	3.810	4.428

TABLE V: Peak-to-peak torque (Nm) with different magnetic and non-magnetic materials

	AISI 1010	AISI 1018	AISI 1020	AISI 430	IMACRO M	MOCN315	S355	X20Cr13	40CrMoV5-1
AISI 304	1.934	1.903	2.034	1.352	1.196	1.499	2.009	1.463	1.881
AISI 316	1.934	1.904	2.035	1.352	1.196	1.499	2.010	1.464	1.826
Creusabro	1.952	1.921	2.053	1.366	1.208	1.513	2.028	1.477	1.843
Inconel 718	1.950	1.920	2.050	1.365	1.202	1.514	2.025	1.478	1.842
Titanium	1.952	1.921	2.051	1.368	1.201	1.517	2.027	1.480	1.844

TABLE VI: Power factor (PU) with different magnetic and non-magnetic materials

	AISI 1010	AISI 1018	AISI 1020	AISI 430	IMACRO M	MOCN315	S355	X20Cr13	40CrMoV5-1
AISI 304	0.651	0.651	0.653	0.637	0.630	0.642	0.653	0.641	0.647
AISI 316	0.651	0.651	0.653	0.637	0.630	0.642	0.653	0.641	0.651
Creusabro	0.652	0.651	0.654	0.638	0.632	0.643	0.653	0.642	0.651
Inconel 718	0.652	0.652	0.654	0.638	0.631	0.643	0.653	0.642	0.651
Titanium	0.652	0.652	0.654	0.638	0.631	0.643	0.654	0.642	0.651

electromagnetic point of view. With similar values of power compared to S355 or AISI 1020. With a high permeability it is possible to reach that speed, but working in flux weakening region with a higher current control angle. This is possible, but introduces a lot of problems for this kind of machine as mentioned in [22], when a higher current angle control is applied the high-order flux density harmonics grow and with them also the eddy current losses, the stator ones, and the torque ripple.

In the choice of the material, another important aspect that should be considered is the mechanical integrity of the structure at a high speed also considering the possible temperature variations. This kind of rotor has two different materials bonded together which are affected by the losses inside the rotor and the thermal heat exchange from the stator. This increases the temperature of these materials which typically have a different thermal coefficient of linear expansion. This produces additional stress in the rotor which may cause its bending, bowing and eventually breaking. For this reason, in addition to the electromagnetic aspects of the materials, the choice of the combination of them should include these aspects.

Titanium that shows the highest electrical resistivity which leads to the highest performance of the material with a low value of density it is not applicable combined with the analyzed materials because it has a very low thermal coefficient of linear expansion compared to the other materials. The combinations that show similar values of thermal coefficient of linear expansion are Inconel 718 (12.8 μm/(m°C)) with AISI 1010 (12.2 μm/(m°C)), IMACRO M (12.0 μm/(m°C)), MoCN315 (12.0 μm/(m°C)), S335 (12.0 μm/(m°C)), and Orvar Supreme (12.8 μm/(m°C)). Between these materials the one that shows the highest torque is the S335 while the one that shows the best efficiency is Orvar Supreme. These are the two most suitable candidates for the combination with Inconel 718. Orvar Supreme shows also higher mechanical properties with tensile strength around 2000 MPa, but this material should be too expensive for some applications compared to the structural steel S355; therefore the choice compromise between these two depends from the maximum strength required by the motor, the maximum torque, and the cost.

V. Conclusions

In the study, nine magnetic steels and five non-magnetic steel materials and their suitability for axially laminated SynRM high-speed electric machine were investigated with 2D electromagnetic FEM. In the comparison the power factor, efficiency, peak-to-peak torque and average torque were evaluated in addition to the electromagnetic properties, the mechanical and thermal properties were considered as well. The study shows that the individual performance criterion are strongly correlated and the final selection of the most suitable pair of materials is highly application specific, i.e. which compromise leads to the best performance. The best solution in terms of efficiency, maximum torque per ampere, and torque density is the adoption of S355 as magnetic material thanks to its high magnetic permeability and high saturation level. The selection of the non-magnetic material needs some additional consideration. From economic point of view titanium presents a higher price per mass compared to Inconel 718, but considering its lower density the total cost for the rotor production is the same. The adoption of titanium allows for higher efficiency thanks to its higher electrical resistivity and higher torque density thanks to its lower density. The limit of this material is the thermal coefficient of linear expansion quite different compared to the one of S335. The best compromise, which includes economic, performance, and manufacturability aspects, is the adoption of Inconel 718 because it has quite much higher performance compared to Orvar Supreme with a reduced price. With this combination, an experimental campaign is under evaluation in order to verify the analytical results.

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